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**UNUSUAL INTERACTIONS  
ABOVE 100 TeV:  
A REVIEW OF  
COSMIC RAY EXPERIMENTS  
WITH EMULSION CHAMBERS**

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Unusual Interactions above 100 TeV: A Review of  
Cosmic Ray Experiments with Emulsion Chambers \*

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# I. Introduction

Up to the present, the only information about characteristics of individual hadronic interactions at energies greater than 100 TeV comes from Cosmic Ray studies of families of so called gamma-jets in emulsion chambers exposed at mountain and balloon altitudes. Since the early sixties emulsion chambers have been exposed at Mt. Norikura (Fujimoto, Y., et al. 1960, Akashi, M., et al., 1965 a,b), Mt. Chacaltaya (Lattes, C. M. J., et al. 1971), Mt. Fuji (Akashi et al., 1975, Ohta et al., 73, Shibata, 75) and in Pamirs (Anischenko et al., 73, Pamir coll.75). Several hundred gamma-families (A space correlated collection of jets in Pb or Fe absorber sampled by photosensitive layers) with total equivalent gamma ray energies in these families ( $\sum E_{\gamma}$ ) greater than 100 TeV and a few tens above 1000 GeV have been observed. These events should give us a glimpse into the energy region which could become accessible with colliding beams within the next decade - center of mass energies of the order of 0.4 TeV or more. It is, however, difficult to interpret these events as the experiments only observe the products subsequent to an interaction (or interactions) and because the nature of the primary is not known (although some plausible arguments can be made as to what it may be!). There are two observations which in my opinion are most unusual; these are:

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1. Possible existence of " $\pi^0$ " less events of high multiplicity.
2. Events with very large multiplicity.

The purpose of this paper is to examine the techniques, describe the unusual events, answer the question "are there normal events?" and estimate the rate for such events. Only for the sake of brevity, details will be omitted but detailed references are given for the reader who wants to pursue them on his own.

The subject of study of very high interactions using emulsion chambers was reviewed earlier by C. B. A. McCusker (McCusker 1975) who discusses the evidence for fireballs, large  $p_t$  and scaling in  $\gamma$ -families.

## II. Cosmic Ray Beam: What event rate one expects at these high energies?

The all particle cosmic ray flux has been directly measured in satellites up to 100 TeV (Akimov et al. 1969) and indirectly by observing extensive air showers (EAS) from 1000 TeV upwards up to  $10^8$  TeV. Although, the composition of this beam has not been measured beyond 5 TeV (Balasubrahmanyam et al. 1973) one can estimate the flux of all nucleons in cosmic rays to be (within a factor of 3) given by  $J(>E, x=0) = 3 \times 10^6 E^{-1.6} (\text{m}^2 \text{ sr year})^{-1}$  where  $E$  is the energy per nucleon in TeV up to 1000 TeV. This implies that  $J(>100 \text{ TeV}, x=0) = 1500 \text{ P/m}^2 \text{ sr year}$ . To calculate the flux of events with observed energy  $> 100$  TeV into  $\gamma$ -rays in an emulsion chamber at Mt Chacaltaya ( $x = 550 \text{ g/cm}^2$ ) one must evaluate:  $J(>\bar{E} E_\gamma = 100 \text{ TeV}, x = 550) = \exp(-550/\Lambda) k_\gamma^{1.7}$   
 $J(>100 \text{ TeV}, x=0)$  where  $\Lambda$  is the attenuation mean free path for hadrons at 100 TeV and  $k_\gamma$  is the energy going into EM component. If we take  $k_\gamma = .17$  (Hayakawa S., 1969) and assume a rising nucleon-air cross section to estimate  $\Lambda = 111 \text{ g/cm}^2$ , one obtains for the expected flux  $J(>\bar{E} E_\gamma = 100 \text{ TeV}, x = 550) \approx 0.55 \text{ p/m}^2 \text{ sr year}$ . Typical E. C. exposure at Mt. Chacaltaya is  $\sim 30 \text{ m}^2 \text{ sr year}$ , here one expects  $\sim 15$  events per exposure with  $\Sigma E_\gamma \geq 100 \text{ TeV}$ .

This is in good agreement with observations. (A more detailed estimate is given in appendix). We, therefore, believe that the E.C. experiments have a reasonably high efficiency for detecting these very high energy events. The events observed are probably produced within an interaction length above the chambers or in the chambers themselves. The flux of events due to interactions of heavy nuclei which have survived to depth of a kilometer or so above the detector can be shown to be negligible. Consequently, we believe that events to be discussed in this paper must have been produced in the hadron-air collisions (where the hadron is a nucleon, pions or kaons) within a kilometer ( $\sim 100 \text{ g/cm}^2$ ) above the detector. Typical fluxes of events with high  $\Sigma E_Y$  have intensities given by ( $x \sim 600 \text{ g/cm}^2$ )

$$1000 \text{ E}^{-2} \text{ p/m}^2 \text{ sr yr}$$

(see Figure 1).

### III. Emulsion Chamber Detectors:

#### A. Physical Description:

The basic detector consists of a sandwich array of lead and emulsions. As a typical detector I discuss the structure of chamber number 17 of the Japan-Brazil group at Mt. Chacaltaya, shown in figure 2 (Tamada 1976). It consists of upper and lower chambers and produced layer of cans of pitch. There is about 200 cm separation between the chambers. The upper chamber is a layered stack of lead with a first set of X-ray films after 3 cm of lead followed by X-ray films every 1.0 cm of lead. Total thickness of lead is 10.5 cm or 19 radiation lengths, and 0.58 interaction lengths. The producer layer is 21 cm of pitch corresponding to 0.34 rad lengths and 0.50 interaction lengths. The lower chamber consists of 7 cm of lead with 8 sensitive layers. A typical sensitive layer consists of 3 X-ray films (one of RR type and two NN type) and one 50 cm FUJI MA7B emulsion. There are some layers in the upper chamber with only 2NN type x-ray films. The total area covered by these emulsion chambers at Mt. Chacaltaya (5200 m asl/ or  $550 \text{ g/cm}^2$ ) is about 40 square meters (geometric

factor  $\sim 30 \text{ m}^2 \text{ sr}$ ) and are exposed for about one year. The total exposure factors with emulsion chambers (each of different type) are approximately.

TABLE I

Location	Altitude ( $\text{g}/\text{cm}^2$ )	Exposure
Mt. Fuji	650	$498 \text{ m}^2 \text{ sr yr}$
Mt. Chacaltaya	550	$\sim 150 \text{ "}$
Ch (14, 15, 17)		
Pamirs	600	$\sim 260 \text{ "}$

Using the flux at Mt. Chacaltaya, (estimated in the previous section) one can estimate that about 40 events with  $\Sigma E_{\gamma} \geq 100 \text{ TeV}$  with an  $E^{-2}$  spectrum should have been detected. (This implies 10 to 11 events above 300 TeV).

#### B. Method of Observation:

The X-ray films are examined for the presence of dark spots or families of dark spots which are caused by ionization due to particle densities of the order of  $0.1$  to  $10 \text{ particles}/(\mu\text{m})^2$ . Such particle densities are realized when an electromagnetic cascade shower is developed in the lead-emulsion sandwich by energetic electrons or photons. The energy threshold for observation of a dark spot depends on the level of background darkness in the X-ray film, its developed grain size and sensitivity. The thresholds for detection vary from chamber to chamber between  $200 \text{ GeV}$  and  $1000 \text{ GeV}$ , so that for most experiments efficiency for detection of dark spots is unity above  $1 \text{ TeV}$ . (Ohta, I., 1971; Akashi, M., et al. 1964).

Every dark spot or families of dark spots is followed through layer by layer to make the following measurements:

1. Direction of propagation
2. Cascade curve (longitudinal development) of each spot (Darkness measurement)
3. Lateral spread of each spot

4. Separation of individual spots in a family as a function of depth
5. Track count in each nuclear emulsion layer for each spot

C. Classification of dark spot Cascades:

Each dark spot cascade is called a "jet". A jet or a jet family can be caused by different sources. These are tabulated below (see also Figures 3 and 4).

<u>Source</u>	<u>Observed Phenomena</u>	<u>Special Distinguishing Features</u>
Single $e$ or $\gamma$	Single $\gamma$ jet	Characteristic EM Cascade.
Single $\pi^{\pm}$ , N	Pb jet	Delayed start, long nuclear EM cascade.
Single $\pi^{\pm}$ , N	C jet	No jet in upper chamber, a jet family in lower chamber pointing to absorber.
Several $\gamma$ or $e$ " $\pi^{\pm}$ or N	A jet	An interaction in air making a space associated jet family.
Several $\gamma$ 's or $e$ only	A jet	An atmospheric EM Cascade from photon or electron.

The morphology of electromagnetic and hadronic components (Hayakawa, S. 1964) can be studied by measuring the energy dependence of the fluxes of Single  $\gamma$ 's or electromagnetic A jets and of Pb jets plus C jets plus A jets respectively. Spectra are known up to 100 TeV.

Characteristics of individual high energy interactions can be investigated in a clean manner by studying the energy-lateral distributions of jets in C-jets. This has been done in an energy range between 5 and 100 TeV.

Finally, by selecting A-jets with lateral spreads and energy couplings consistent with an interaction in air close to the detector (within one kilometer or 0.5 interaction length and 1 cascade unit) one extends the study of high energy interactions up to about 1000 TeV.

The results from C-jets and A-jets pertinent to the question of scaling up to 1000 TeV will be discussed in another paper. In this paper we describe the observation of several very unusual events above 100 TeV which indicated the existence of new phenomena hitherto not expected.

#### D. Determination of energies of Jets:

Two methods are employed in determining energies of the jets:

1. Measurement of spot darkness in X-ray films and
2. Measurement of track count in nuclear emulsions.

These methods are described in detail in several papers (Ohta, I. 1971 and Akashi, M. et al. 1964).

Typical dark spots have a 50  $\mu\text{m}$  size. The darkness is measured using a slit of radius  $\sim 50\text{-}150$   $\mu\text{m}$  relative to the background darkness by a transmission technique. The darkness  $D$  is a function of energy  $E_0$  of the initiating particle, depth  $t$  of observation along the cascade curve and slit size  $R$ . For cascades initiated by electrons or photons (approximation A can be used because the energies of the electron within 50  $\mu\text{m}$  must be greater than 7 GeV) one can show that maximum spot darkness,  $D_{\text{max}}(E, R)$ , has the functional dependence.

$D_{\text{max}}(E_0, R) \propto (E_0/R)^\beta$  where  $\beta$  has been determined to be  $0.85 \pm .05$  using 650 MeV  $e^-$  beams from a Synchrotron. Furthermore, a direct check was carried out with the track counting method between 1 and 20 TeV. The final accuracy obtained for energy estimation is  $\pm 15\%$ . For cascades initiated hadrons, the method only measures energy going into EM component. Darkness is measured first outside the central core for these jets where the electron density follows that of purely EM cascades. The resulting darkness longitudinal profiles are compared with those of EM cascades to obtain a measure of energy in EM component in a hadronic jet (Pb jet). Again energy estimations by maximum spot darkness method are compared with track count method to obtain a calibration curve for EM energy in Pb jets. The estimated accuracy is again shown to be  $\pm 20\%$ .

It is worth pointing out, first, that results from different groups (Pamirs, Mt. Fuji and Mt. Chacaltaya) as to the absolute flux of single hadrons are internally consistent. Secondly, and more importantly, the measured hadron



fluxes by large and deep calorimeters for single hadrons at mountain altitudes (Aseiken, et al. 75, Siohan 75) when converted for altitude and  $K_y$  give results that are in reasonable agreement with Emulsion chamber measurements. Emulsion chamber fluxes are higher by a factor of five above the calorimeter measurements, which is to be expected as emulsion chambers measure the all nucleon flux, whereas the calorimeters measure single unaccompanied hadrons.

### III. Method of Analysis and Selection of Atmospheric $\gamma$ -families: (A-jets).

#### A. General Considerations:

Clusters of jets or  $\gamma$ -families are selected by visual scanning of the X-ray films of the upper and lower chambers. A typical family will consist of several spots juxtaposed with maximum spread of less than 10 cm. The number of single jets of energy  $\sim 3$  TeV in  $100 \text{ cm}^2$  in one year is  $\sim 0.3$ , thus the chance of finding 4 random jets within  $.01 \text{ m}^2$  is less than .01. In addition the jets are required to have same zenith and azimuth to  $\pm 3^\circ$  and  $\pm 10^\circ$ . This completely eliminates background for chance juxtaposition. It is therefore clear that clusters with  $\bar{E}E_\gamma$  of the order of 10 TeV and spread  $< 10$  cms in the upper chamber will not be contaminated by "background" due to single  $\gamma$ -rays. At higher energies this background is even smaller.

Cascades in each cluster are followed through successive layers to determine arrival direction and energy. C-jets are selected by finding a family in lower chamber, pointing it towards the upper chamber and determining whether there does exist a family in upper chamber in the right location and in the right direction. An additional constraint put on the selection of C-jets and A-jets is that the number of jets in a family should be greater than 4. This eliminates single  $\pi^0$  events. A-jets are selected by finding a family in the upper chamber with the following further restrictions:

(1) Estimated height of the hadronic interaction from which A jet was created should be between 100 m and 1000 m. This means that the lateral spread of the cluster of jets must be between 0.5 and 10 cms in the upper chamber. The spread of A jets with interaction height of  $\sim 10$  m will have a lateral spread which is about the same as that due to an air electromagnetic cascade from a single energetic photon or electron originating several Km's higher in the atmosphere, such jets would have very small spread. The lower limit to lateral spread helps reduce the background due to such processes.

(2)  $\gamma$ -families with obvious indication of cascading are rejected.

#### B. Estimation of Height:

Estimation of height of interaction of A jets is carried out by three different methods and consistency among them is required. These are:

- (1) Coupling pairs of  $\gamma$  jets.
- (2) Cascade development of "unpaired"  $\gamma$  rays.
- (3) Increase of lateral distance between hadronic jets with depth.

In the first technique, if  $E_1, E_2$  are the individual  $\gamma$  energies of a coupled pair with separation  $L$  then height of origin is given by  $H = L \sqrt{\frac{E_1 E_2}{Mc^2}}$ .

If estimation by this method gives the same value of  $H$  (within errors) for two different  $\pi^0$  origins then interaction height is estimated.

In the second technique, the number of  $\gamma$ -rays jets arrived at upper chamber without pair creation ( $N$ ) are compared with total number ( $N_0$ ) to estimate  $H$  by the formula  $N = N_0 \exp(-H/771) \text{ m}$ .

In the third method, one finds increase in lateral separation with depth in the chamber to get a point of origin.

C. How does one estimate the energy of incident particle?

What is measured is  $\bar{\Sigma}E\gamma$ . For  $\pi^0$  s,  $\gamma$ -jets measure the full energy of  $\pi^0$ . For other hadrons, however, the Pb-Emulsion chambers measure the energy going into the EM component (via presumably  $\pi^0$ ). So observed energy  $\bar{\Sigma}E\gamma$  is equal to  $K_{\gamma}E_0$ , where  $K_{\gamma}$  is the inelasticity into EM component. The true energy of the hadronic interaction being studied is always greater than observed energy. It must also be remembered that  $K_{\gamma}$  fluctuates substantially from event to event and in general depends on the nature of the hadron i.e. whether it is a pion or a nucleon.

D. Number of events with  $\bar{\Sigma}E\gamma > 100$  TeV observed in Chacaltaya emulsion chambers 14, 15, and 17.

The exposure factors for these chambers are about 47, 35, and 68 m<sup>2</sup> sr year respectively. From figure 1, one can estimate that total # of jets with  $\bar{\Sigma}E\gamma > 100$  TeV that should have been recorded must be about 40 events with an  $E^{-2}$  spectrum.

IV. Unusual Events Above 100 TeV:

Below  $\bar{\Sigma}E\gamma$  of 100 TeV but above 10 TeV many events have been collected and analyzed. It will be shown in another paper (Gaisser 77) that in general these events are consistent with scaling in the fragmentation region, but indicate a more rapid rise in multiplicity than required by scaling models in the plateau region.

Above 200 TeV, however, only a few "pure" A-jets have been observed and even fewer completely analyzed. Those analyzed form a substantial fraction of the total number observed. (at least 20%). All the analyzed events have one or more of the following unusual features,

- (a) Have large multiplicities of particles in the primary hadron - air interaction.

(b) Show a marked absence of neutral pions.

(c) Have visible energies,  $\bar{\Sigma}E_{\gamma}$  greater than 200 TeV.

As pointed out in section I, these events, produced in close proximity of the detector, cannot be due to heavy nuclei based upon flux considerations. Therefore, it would appear that we are observing really new phenomena with a very large cross section above 100 TeV.

(A) "Centauero" events:

(1) Method of Search and Overall Characteristics:

The name centauro for these events was coined because the clusters found in lower chambers of CH-15 had apparent shape of a "Centuarus"! It is an event which when analyzed involves a hadron-air collision of  $E > 250$  TeV producing more than 90 hadrons and no  $\pi^0$ 's!

An interaction of this type is selected by finding a family in the lower chamber whose direction extrapolates back through the upper chamber and whose lateral spread in the lower chamber is such that one has high likelihood of dealing with an event arising from an air interaction within 1000 meters of the chamber. The complete development through the emulsion chamber is analyzed in terms of jets and the jets are classified as to whether they are (1) EM jets in the upper chamber, (2) Pb-jets in upper chamber, (3) C-jets from the producer and (4) Pb-jets in lower chamber. (See figures 3 and 4 for description). The following table gives the characteristics of 4 events so far detected labelled CH15-1, Ch17-1, Ch17-2 and Ch17-3. Up to the present time results of detailed analysis have been published only for CH15-1 and Ch17-1 (Tamada, M. 1976). Jets are labelled according to location of their origin and their nature. For events CH15-1 and CH17-1, 7 Pb jets and 3 Pb jets respectively, originate in the upper chamber and penetrate through the producer layer to show up in the lower chamber.

TABLE II  
Catalogue of "Centauro" Events

Event No. (Total Ev.)	Lateral Spread in Lower Chamber cm	Upper Chamber		Pb-jets Penetrating to Lower Chamber	Lower Chamber	
		Atm. Electrons & $\gamma$ -rays $\gamma$ -jets	Pb jets		C-jets	Pb jets
15-1 (231 TeV)	1	1(9 TeV)	6(19.1 TeV)	7(33 TeV)	29(155 TeV)	7(15 TeV)
17-1 (284 TeV)	10	61(142 TeV)	15(54 TeV)	3(69 TeV)	13(68 TeV)	7(14 TeV)
17-2	5		18		14	
17-3	1		9		20	

Sketches of Ch-15-1 and Ch17-1 are shown in figures 5 and 6. These must be treated as illustrations, the vertices of individual jets not in the upper or lower chambers only indicate in which region their origin must be located - air or producer layers.

Examples of observed cascade curves for Pb-jets starting below 8 c.u are shown in figure 7 (Tamada 76). The superposed curves are cascade curves for electromagnetic jets which are used to estimate the total visible energy of each Pb-jet. The top jet has an equivalent  $E_\gamma$  of 8.4 TeV and the lower one 6.2 TeV. A single EM cascade of 8.4 TeV would look very different from Pb-jets cascade.

(2) Determination of height of atmospheric Interaction:

(a) CH15-1

Interaction height was determined in two ways. One method was to measure the divergence of a pair of Pb-jets which showed clear spots in both upper and lower chambers. Mutual distance between the spots in 7 mm and the increase in distance between the spots in the lower chamber was  $0.25 \pm .05$  mm. This gives an estimate of the production height of these two hadronic jets to be  $50 \pm 15$  meters. In the second method the divergence of family in lower chambers is estimated by measuring the average fractional increase in depth along the cascade. This gives  $50 \pm 20$  m for estimation of production height.

(b) Event CH17-1

In this event the height of production was estimated by comparing the apparent transverse momentum distribution with that of Ch15-1, event. One constructs the quantity  $E_\gamma \cdot r$ , where  $r$  is the distance from energy weighted center for each Pb-jet and C-jet and plots  $N(>E_\gamma \cdot r)$ . If all hadrons come from the same vertex than  $r \propto \left( \frac{\langle p_\perp \rangle}{E_h} \right) H$ . Noting that  $E_\gamma = k_\gamma E_h$ ,  

$$H \approx \frac{E_\gamma \cdot r}{k_\gamma} \cdot \frac{1}{\langle p_\perp \rangle}.$$
The integral spectra for CH15-1 and CH17-1 for  $N(>E_\gamma \cdot r)$  verses  $E_\gamma \cdot r$  are compared in figure 8. They are in good agreement with each

other and can be used to obtain  $H=520 \pm 100$  m.

### (3) Establishing the unusual nature of the events

Having estimated the height of production one can try to understand the longitudinal distribution observed jets in these events in terms of nature and number of the particles produced in the primary interactions. We assume that the produced hadrons have normal characteristics as regards to their life times and interaction with matter. The observed number of Pb jets and C jets can be used to predict the number of hadrons ( $\pi^+$  and p, n,  $\bar{p}$ ,  $\bar{n}$ . . .) incident on the chamber, and number produced in the air interaction. To illustrate how this is done the chambers are displayed in figures 9 and 10 in terms of interaction lengths. The percentage of hadrons other than  $\pi^0$ s, which must interact in various regions are shown. For CH-17-1,  $90 \pm 10$  (other than  $\pi^0$ s') should be produced at the interaction vertex. If these hadrons were mainly charged pions and if isospin conservation holds, then 35  $\pi^0$ s' and 45  $\pi^0$  respectively should have been produced in CH15-1 and CH17-1 interactions. These in turn should have given rise to 70 and 90  $\gamma$ -jets respectively in the upper chamber which should have been observed. For CH15-1, only one was observed. For CH17-1, 61 were observed (see Table II). In the latter case, 61 observed are consistent with the number of secondary A jets that must exist because of interactions of the 90 hadrons during their travel through 500 meters of air. Therefore, even for CH17-1 there is obvious lack of  $\gamma$ s' from the original interaction.

We have found no reasonable hypothesis which could explain the peculiar features of these events as due to some combined effect of fluctuations and presence of cascading. For example, if KNO fluctuations are assumed, probability of obtaining an event with 1 neutral pion is about one percent at these energies. Two consequences of such a fluctuation would be (a) in the same exposure there should have been observed 100 times as many normal events seen, which is not the case and (b) this event would have to have a multiplicity of nucleon-antinucleon

pairs which is very high and unusual.

Successive collisions of a few hadrons giving rise to a "large" lower chamber family is also ruled out because the resulting jets would not be separated by more than 100  $\mu\text{m}$  and hence could not give the observed separations of jet clusters which are more than 10 times larger.

Fluctuations in the number of secondary collisions in the atmosphere of hadrons produced in the primary could lead to fewer  $\gamma$ -rays being detected, however, for event CH-15 the already small probability of interaction in 50 meters of air will not alter the conclusion as to the lack of  $\gamma$ 's. For event CH-17, even if all the 40 nucleons did not interact in the 0.46  $\lambda$  of air there would be a discrepancy between calculated and observed  $\gamma$  rays in the upper chamber. An additional point is that secondary and tertiary hadrons or  $\gamma$  rays will tend to have energies which are low, and may be below threshold of detection.

(4) Total # of particles from interaction, their average

$\langle P_t \rangle$  and Mass of "Fireball"

The Japan-Brazil collaboration have fitted the integral distribution for energy of each hadron to a semi-empirical formula

$$f(E_n/E_0) dE_n = N_n^2 e^{-N_n E_n/E_0} dE_n/E_0$$

which works well, in order to obtain estimate of the total number of hadrons produced in the primary collision. These distributions are shown in figure 11. They give  $N_n = 118 \pm 15$  for CH17-1 and  $94 \pm 8$  for CH15-1. If one further assumes that  $k\gamma = 0.2 \pm .05$  then  $\langle p_t \rangle = 1.7 \pm .7$  GeV/c. and (for the lack of any other reasonable hypothesis) that all of these particles are nucleon then average energy of each nucleon in fireball rest frame is  $2.3 \pm .3$  GeV. It should be remarked that data are consistent with isotropic emission from a fireball moving with  $\gamma \sim 10^4$  as determined from an F-plot (Hayakawa, S. 1969), shown in figure 12. The mass of the fire ball is then of the order of 250 GeV! If such fire balls exist and are produced in pairs their threshold should be about 500 GeV.



(B) Other High Multiplicity events:

It is reasonable to ask: What other types of interactions occur at extremely high energy? What kinds of multiplicities are observed: In Ch17, in the upper block several events characterized by very large multiplicities at energies above  $\Sigma E_{\gamma} > 500$  TeV have been seen (Japan-Brazil collaboration 1971). Previously, two such events at more than 1000 TeV had been reported: Andromeda event - a core of an air shower in early development and Texas Lone Star, an event with multiplicity of 400 and total energy of  $10^4$  TeV found in an emulsion chamber exposed at balloon altitudes (Fowler 1963). Both these events were not "clean", as one was a complicated air cascade and the other could have been produced by a heavy nucleus.

We describe here an event No. 112S in CH-17. It is a large family of jets, spread over only 3 cm, and with  $\Sigma E_{\gamma} = 878$  TeV. There is no general blackening of film between spots which be an indication of diffuse atmospheric cascades. The authors interpret as an A jet originating about 332 m above the chamber and with 100 jets due to atmospheric electrons or gamma rays with  $E_{\gamma} > 2$  TeV and 14 Pb jets with  $E_{\gamma} > 2$  TeV produced in  $1/5$  interaction mean free path of Pb in upper chamber. The 14 Pb-jets imply that  $\sim 70$  hadrons must have been incident on the chamber. The 100 atmospheric jets have varied core structure as shown below:

No. of											
cores	1	2	3	4	5	6	7	8	9	10	Total

No. of											
atm. jets	65	18	8	4	2	1	0	1	0	1	100

A core structure can arise due to either cascading in the atmosphere of  $\gamma$ -ray or an electron and also due to correlations between jets due to  $\pi^0$  decay.

The height of production was determined three ways (see Section II): (i) By relating the number of single core jets to total number  $N = N_0 e^{-H/771m}$ , this

gives  $332 \pm 56$  m for H; (ii) By relating the double core pair separations to height of production assuming that it arises due to pair production separation and subsequent scattering; this gives  $H \sim 250$  m, and (iii) Coupling of gamma pairs into  $\gamma$  s' (more than 30 pairs) gave  $175 \pm 18$  m. Thus we can assume a nearby pure interaction for this event.

Next one can estimate  $\langle p_{\perp} \rangle_{\gamma}$  knowing H, r and  $E_{\gamma}$ . This comes out to be  $\sim 650$  MeV/c which is quite large compared to low energy data.

The angular distribution of  $\gamma$  -rays and Pb jets, plotted as a F-plot indicates that the particles can be constructed to be coming from isotropic decay of a fireball with Lorentz factor of  $10^4$ . Assuming an  $\langle p_{\perp} \rangle \sim 630$  MeV the mass of the fireball visible as  $\gamma$  rays is 876 GeV and if we take  $K_{\gamma} \sim .3$  this gives, again  $M \sim 200$  GeV.

Furthermore, in this event we have estimated about 70 hadrons being produced in the primary interaction. For a "normal" interaction there should be 35  $\pi^0$  produced and hence 70 jets, where in fact 100 were observed. Thus apart from having a very high multiplicity this could be one of the more normal events!

#### V. Discussion:

Let us ask, once again, what is unusual about these events at  $\sqrt{s} > 100$  TeV? In figure 13 we show  $\langle N_c \rangle$  as a function of energy using different extrapolations. At 100 TeV the highest multiplicity from an  $E^{1/4}$  law may be as large as 30 in pp collisions. For p-air collisions this could become 39. How likely is it to get a multiplicity of 100? This likely to occur with a fractional cross section of 0.1 percent! (We are using the observation in section I that in studying close by A-jets we are studying hadron-nucleus collisions).

The main conclusion that we can derive from this graph is that charged particle multiplicities should grow faster than  $a + b \ln s$  above 5 TeV, indicating that new channels are being opened up.

In section II we argued that the number of events being observed by these emulsion chamber experiments are consistent with the expected number, hence these experiments are not singling out only exceptional events but rather represent a reasonable sample of interactions above 100 TeV. It is likely that one is observing new phenomena which could be accessible at ISA energies for controlled studies. I hope that this survey may provide guidance in the design of future experimental facilities at the ISA.

#### Acknowledgments

I would like to thank Drs. T. K. Gaisser, V. K. Balasubrahmanyam and R. W. Ellsworth for many valuable discussions and the kind hospitality of Dr. F. B. McDonald at the Laboratory for High Energy Astrophysics during my sabbatical. The work was supported in part by NSF Grant No. PHY77-01438.

Appendix: To estimate expected  $\Sigma E_\gamma$  spectrum from the primary all nucleon spectrum.

The  $\Sigma E_\gamma$  spectrum is a measure of hadron spectrum arriving at observation depth (called  $y$  g/cm<sup>2</sup>). At energies above 1 TeV we can neglect pion decay and we also neglect kaons. A straight forward solution of diffusion equations is possible if one assumes scaling and constant cross sections (see e. g. Kasahara, K. and Takahashi, Y., 1975). One obtains the following expressions for ratio of all hadron flux to primary nucleon flux

$$(J_\pi + J_N)/J_0 = \frac{Z_{n\pi}}{\lambda_n} \frac{\Lambda_\pi \Lambda_n}{\Lambda_\pi - \Lambda_n} e^{-y/\Lambda_\pi} \left( 1 - e^{-y \left( \frac{\Lambda_\pi - \Lambda_n}{\Lambda_\pi \Lambda_n} \right)} \right) + e^{-y/\Lambda_n}$$

where attenuation lengths  $\Lambda$  are given in terms of interaction lengths  $\lambda$  and average inelasticities  $Zs'$  in N-Air,  $\pi$ -Air collisions weighted by the spectrum as

$$\Lambda_n = \lambda_n / (1 - Z_{nn})$$

$$\Lambda_\pi = \lambda_\pi / (1 - Z_{\pi\pi})$$

$$\lambda_\pi = r \lambda_n, \quad r > 1$$

$Z_{nn}$ ,  $Z_{\pi\pi}$  and  $Z_{n\pi}$  can be obtained from FNAL and accelerator data weighted by  $E^{-1.7}$  integral spectrum. A plausible set of values are (where inequality indicates the direction for nuclear effects in hadron nucleus collisions)

$$Z_{\pi\pi} \leq 0.29$$

$$Z_{nn} \leq 0.37$$

$$Z_{n\pi} \leq 0.086$$

Value of  $r$  at FNAL energies is 1.38 and the interaction length of protons in air at  $\sim 200$  GeV is  $\sim 90$  g/cm<sup>2</sup>. We know that  $\lambda_{n\text{-air}}$  decreases with energy becoming about  $\lesssim 70$  g/cm<sup>2</sup> at 100 TeV (Siohan, 1976).

We obtain the following table

E	$\lambda_n$	$\Lambda_n$	$\Lambda_\pi$	$\frac{\Lambda_\pi \Lambda_n}{\Lambda_\pi - \Lambda_n}$
1	90	143	175	782
10	80	127	155	703
100	70	111	136	604

At Mt. Chacaltaya altitude,  $y = 550$  g/cm<sup>2</sup> the following table gives  $(J_\pi + J_N/J_0)$

E	$J_\pi/J_0$	$J_N/J_0$	$J_\pi + J_N/J_0$
1	$1.63 \times 10^{-2}$	$2.14 \times 10^{-2}$	$3.77 \times 10^{-2}$
10	$1.18 \times 10^{-2}$	$1.32 \times 10^{-2}$	$2.50 \times 10^{-2}$
100	$7.77 \times 10^{-3}$	$7.05 \times 10^{-3}$	$1.48 \times 10^{-2}$

One further factor must be computed to compare with data which measure  $\Sigma E_Y$ .

If  $K_Y \equiv \Sigma E_Y/E_0$  then all hadron flux must be multiplied by  $K_Y^{+\beta}$  where  $\beta$  is the integral spectral index of primary spectrum  $\sim 1.67$ . It is a reasonable assumption that  $K_Y$  lies between 0.17 and 0.3, thus we get the table (for  $K_Y=0.17$ )

E	$K_Y^\beta$	$\frac{K_Y^\beta (J_\pi + J_N)}{J_0}$
1	0.052	$1.96 \times 10^{-3}$
10	"	$1.3 \times 10^{-3}$
100	"	$7.7 \times 10^{-4}$

In addition, one should keep in mind that at 100 TeV the primary spectrum is only known within factors of 4. The primary flux  $J(E > 100 \text{ TeV}, x=0) \leq 1500 \text{ p/m}^2 \text{ srr}$ . If one requires a smooth connection at 1000 TeV with air shower data then  $J(E > 100 \text{ TeV}, x=0) \approx 700 \text{ p/m}^2 \text{ sr yr}$ .

Thus the total hadron flux at Mt. Chacaltaya at  $E > 100$  TeV should be  $0.54 \text{ p/m}^2 \text{ sr yr}$ . This is within a factor of 2 of observations. Considering the extent of extrapolations, this should be considered reasonable agreement.

There is one more factor which will make the agreement better, that has to do with the fact the  $Z_s'$  are upper limits,

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### Figure Captions

- Figure 1: The observed  $\sum E_\gamma$  spectrum at Mt. Chacaltaya (Japan-Brazil Collab. 1973 b) compared with the calculated flux of all hadrons expected from the knowledge of the primary all nucleon flux (Appendix).
- Figure 2: Schematic of the arrangement of the CH-17 emulsion chamber of the Japan-Brazil group exposed at Mt. Chacaltaya in 1972 for 567 days.
- Figure 3: Sketches defining an atmospheric electron or gamma jet ( $\gamma$  jet), hadronic jets: Pb jet and C jet.
- Figure 4: Sketch of an A jet and of an electromagnetic air cascade jet.
- Figure 5: Sketch of the original 'Centauro' event: CH 15-1
- Figure 6: Sketch of the second analyzed Centauro type event :CH 17-1
- Figure 7: Typical cascade curves for identified Pb jets of  $\gamma$  energy 8.4 and 6.2 TeV.
- Figure 8: Integral spectra of hadrons in the variable  $k_\gamma p_t$ . This distribution is proportional to  $E_\gamma \cdot r$ , where  $r$  is the lateral distance of a jet from the energy weighted center with  $k_\gamma$  as a constant.
- Figure 9: Longitudinal structure of the emulsion chamber for event CH 15-1 indicating the interaction probability for different layers and giving a comparison of expected and observed number of events.
- Figure 10: Same data as in figure 9 for event CH 17-1
- Figure 11: Integral distribution in the variable  $E_h/E_0$  for CH 15-1 (open circles) and CH 17-1 (dots) events.
- Figure 12: F-plots for hadrons in CH 15-1 and CH 17-1 events. The bend in the points for angles greater than  $10^{-4}$  radians is due to detector threshold.
- Figure 13: Average charge multiplicities as a function of energy. The EAS lower bound is model dependent (Wdowczyk and Wolfendale 1973)

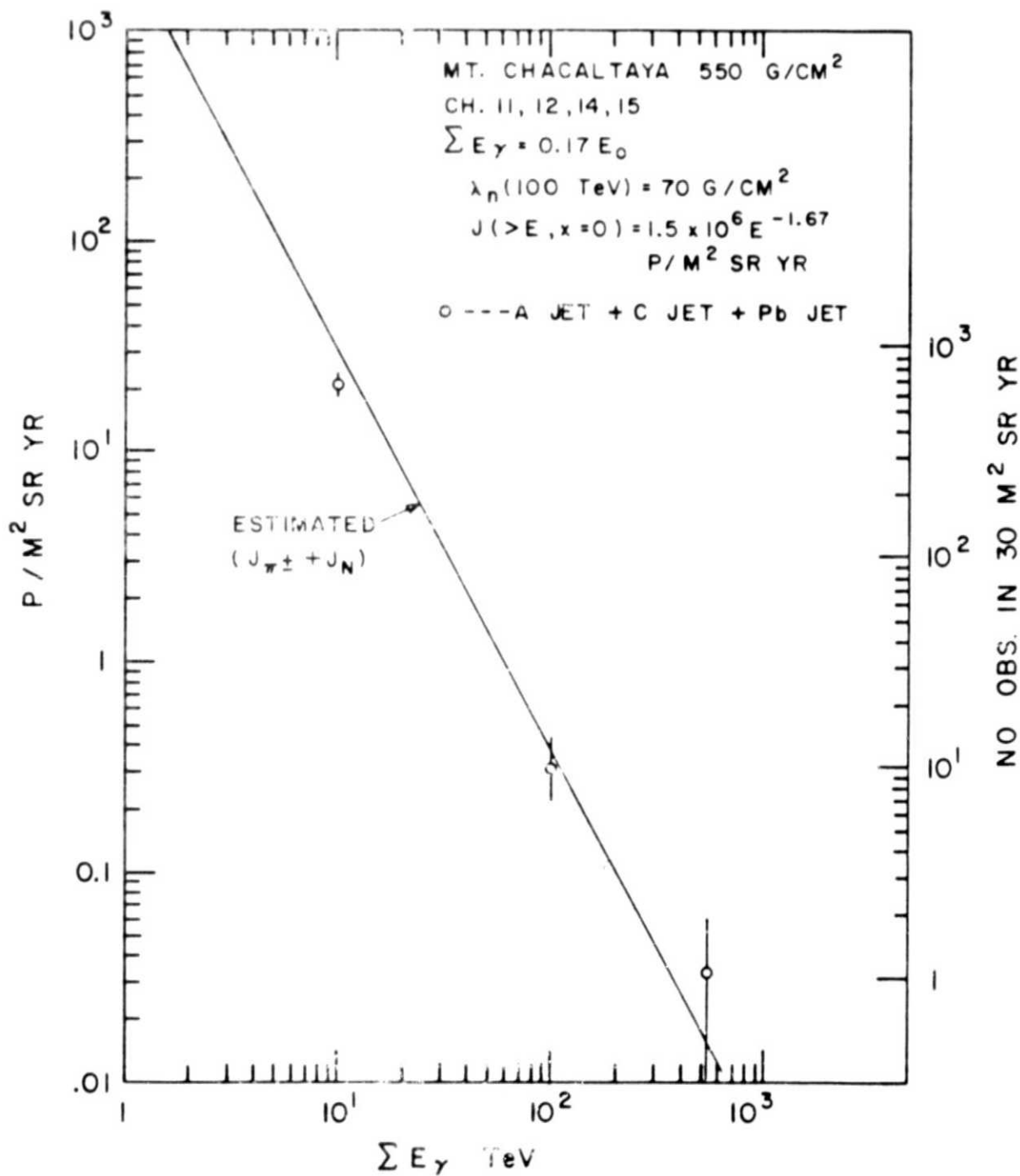


Figure 1

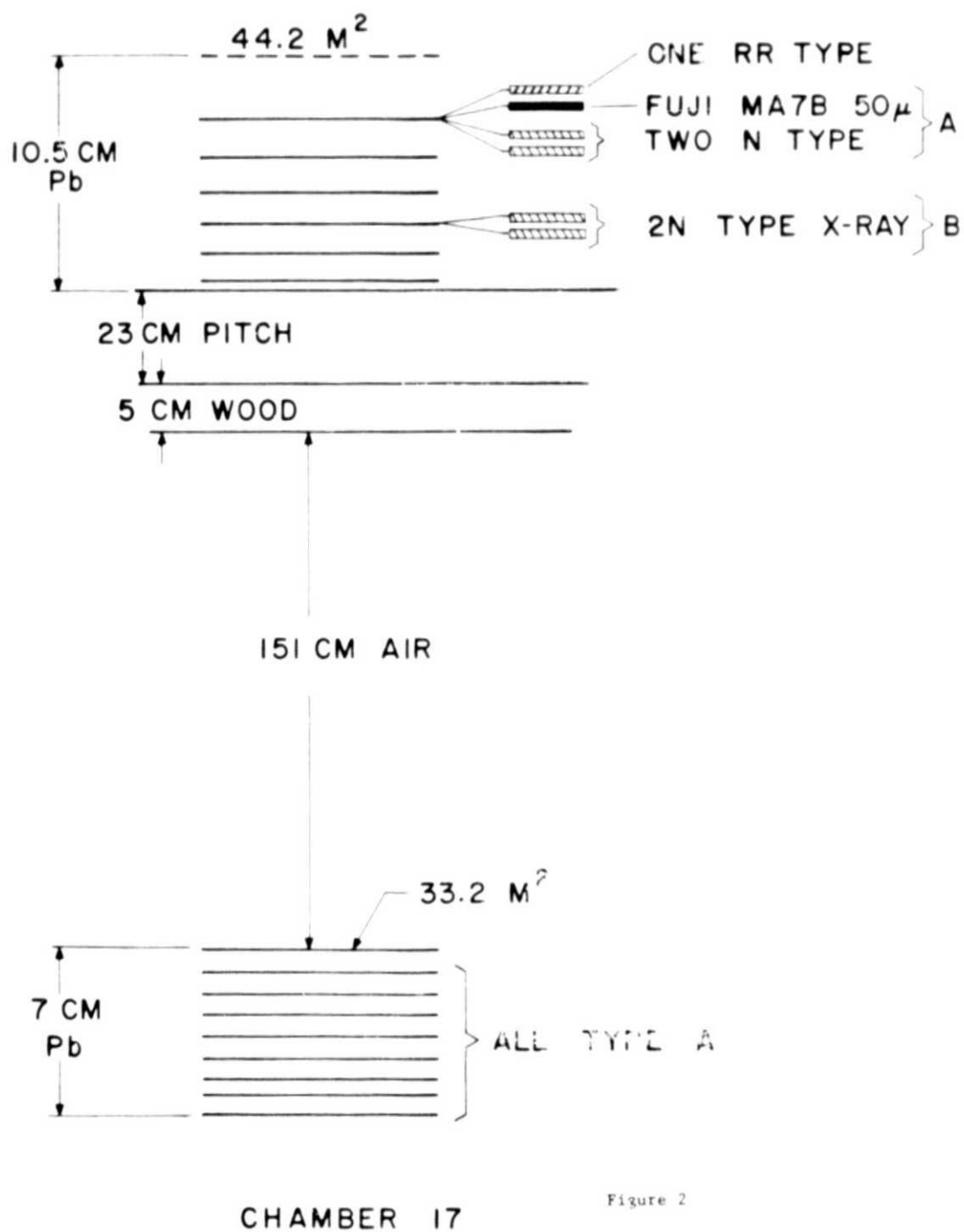


Figure 2

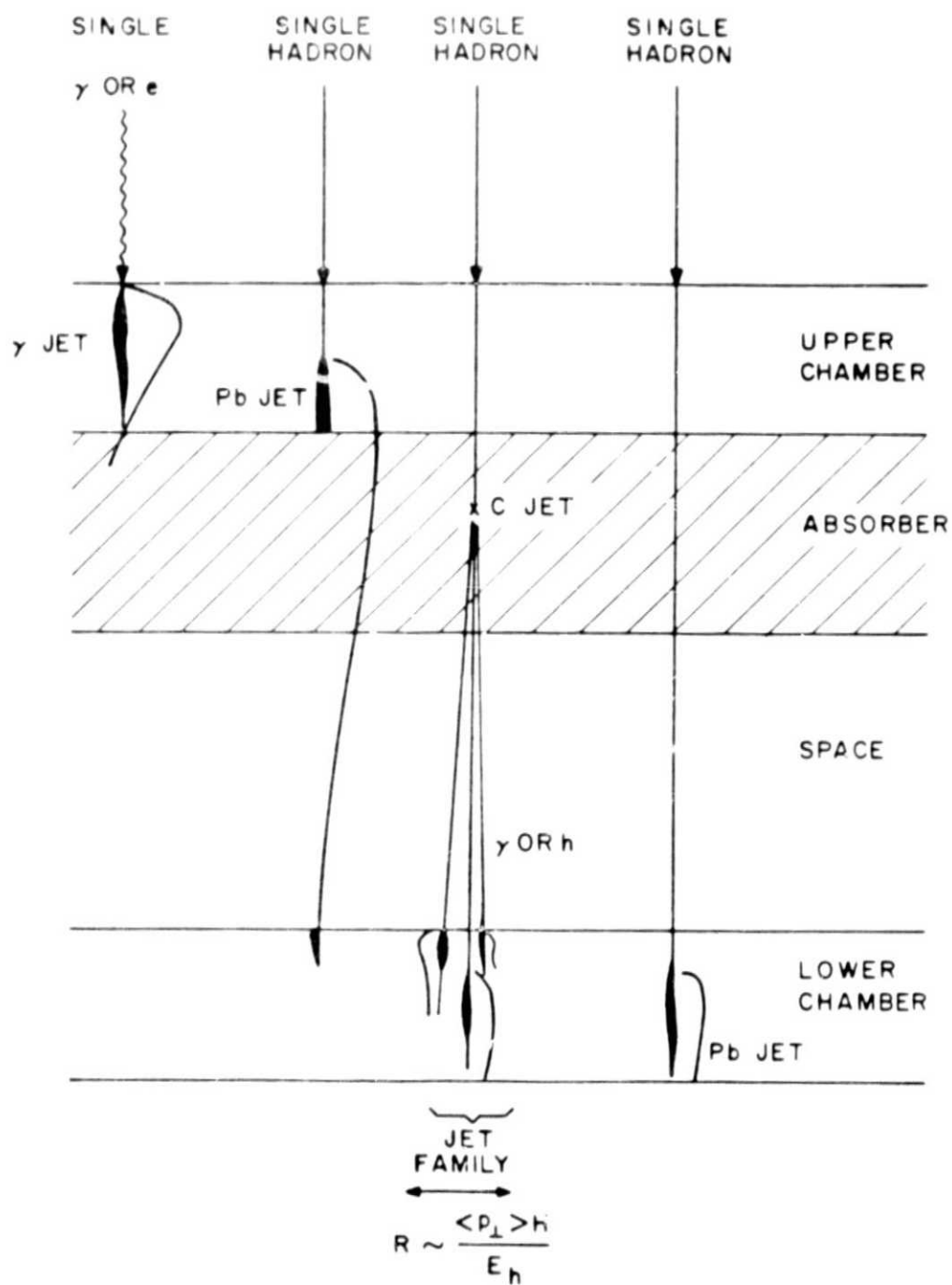


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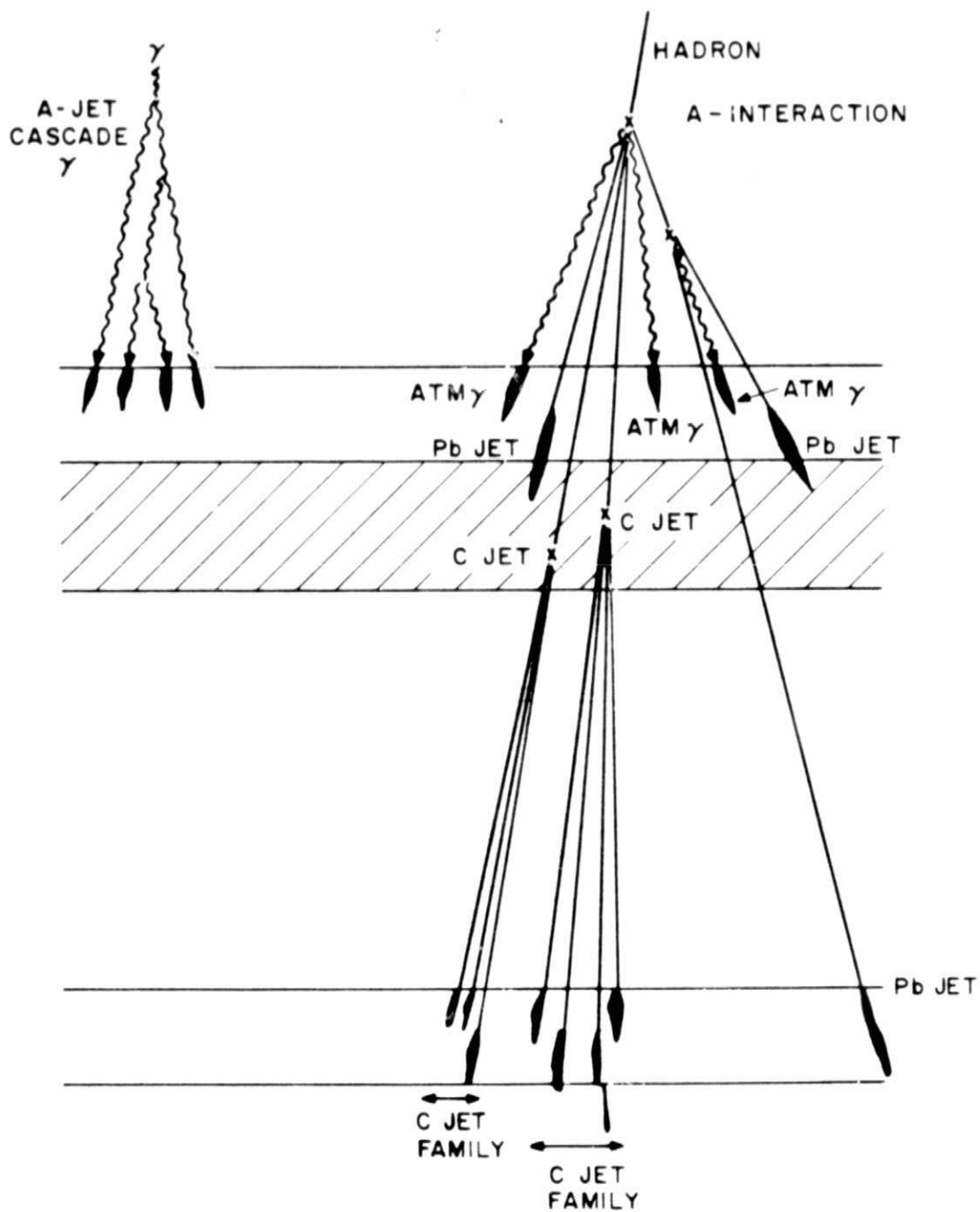


Figure 4

Figure 5

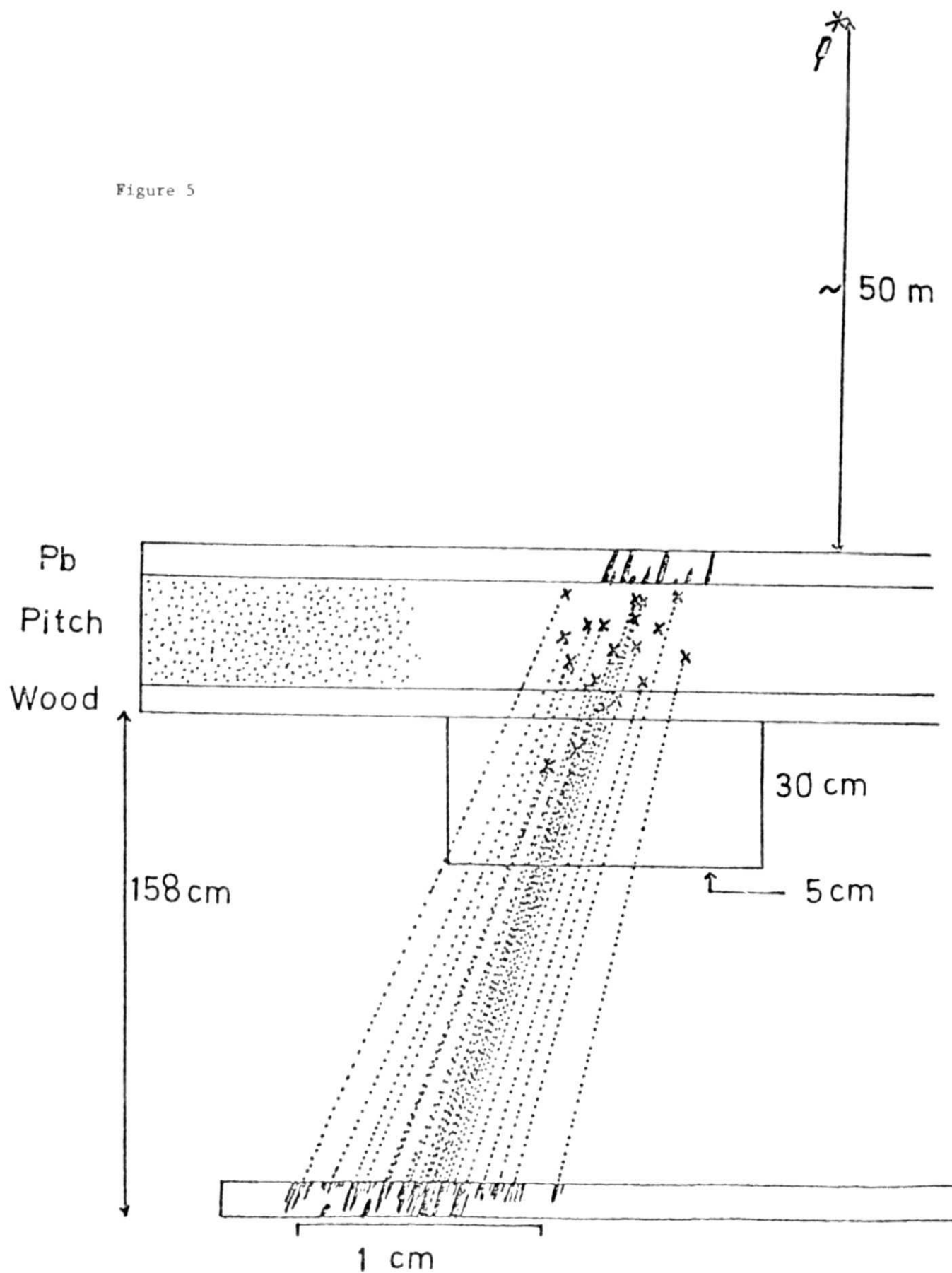
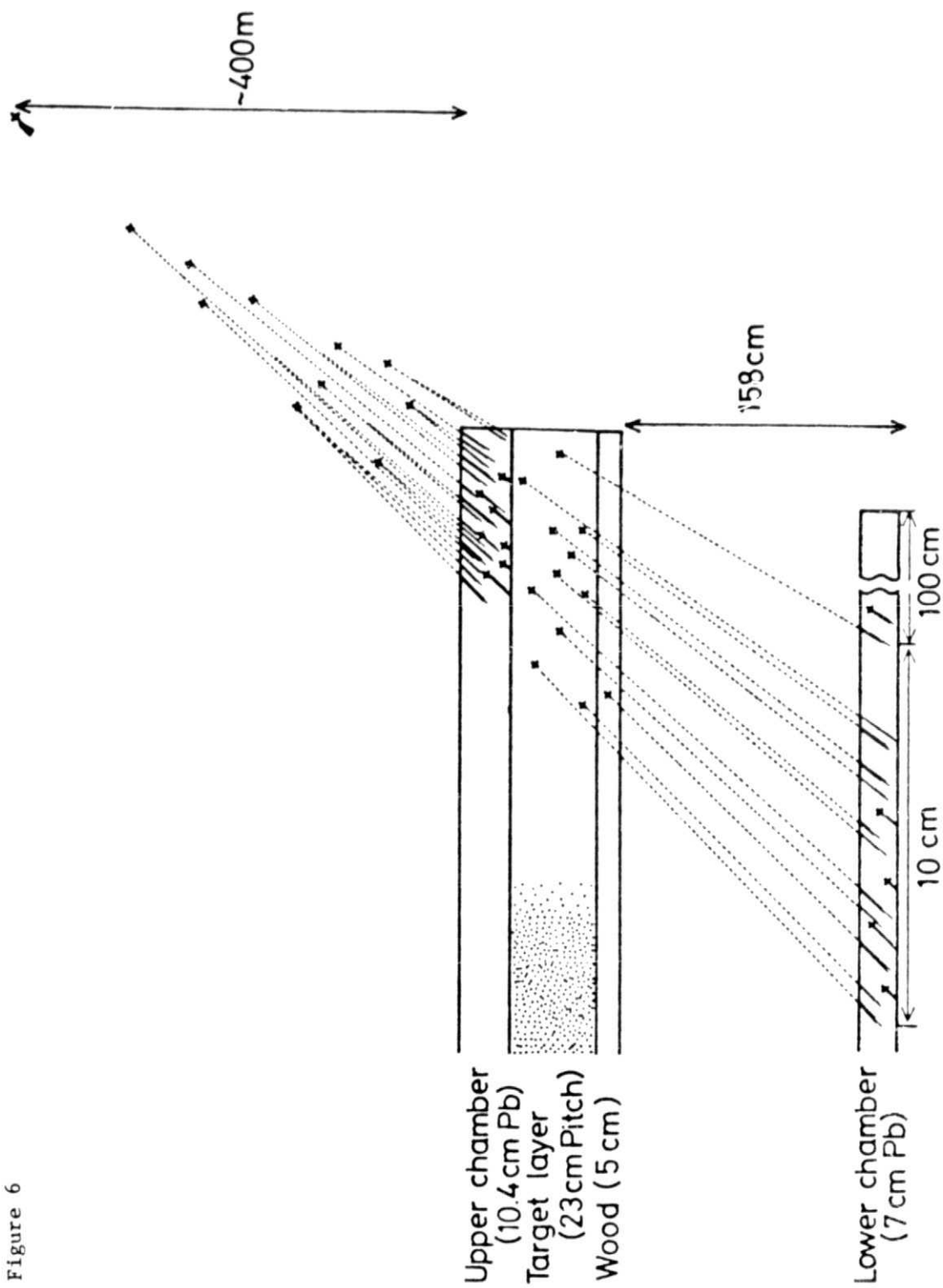


Figure 6



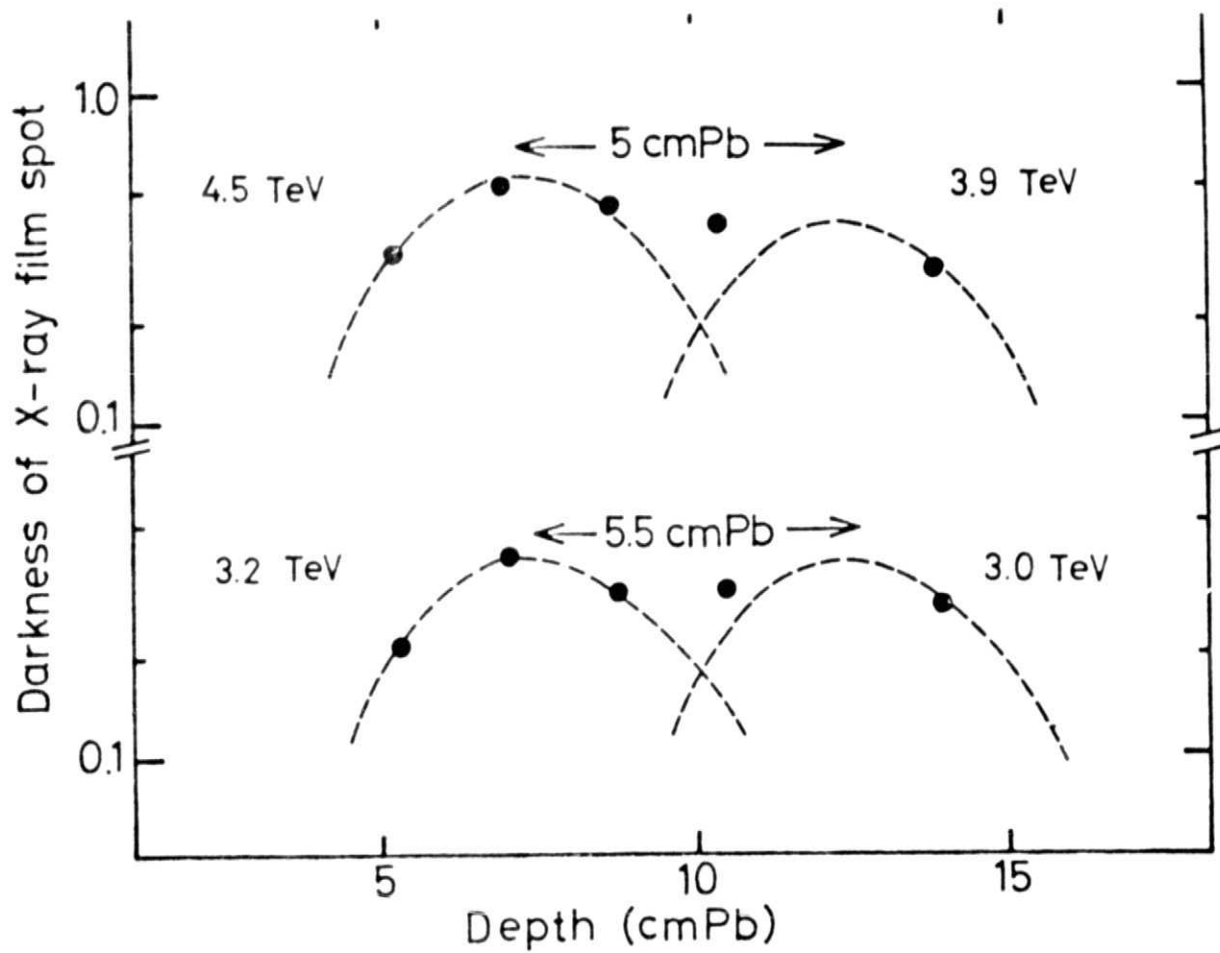


Figure 7



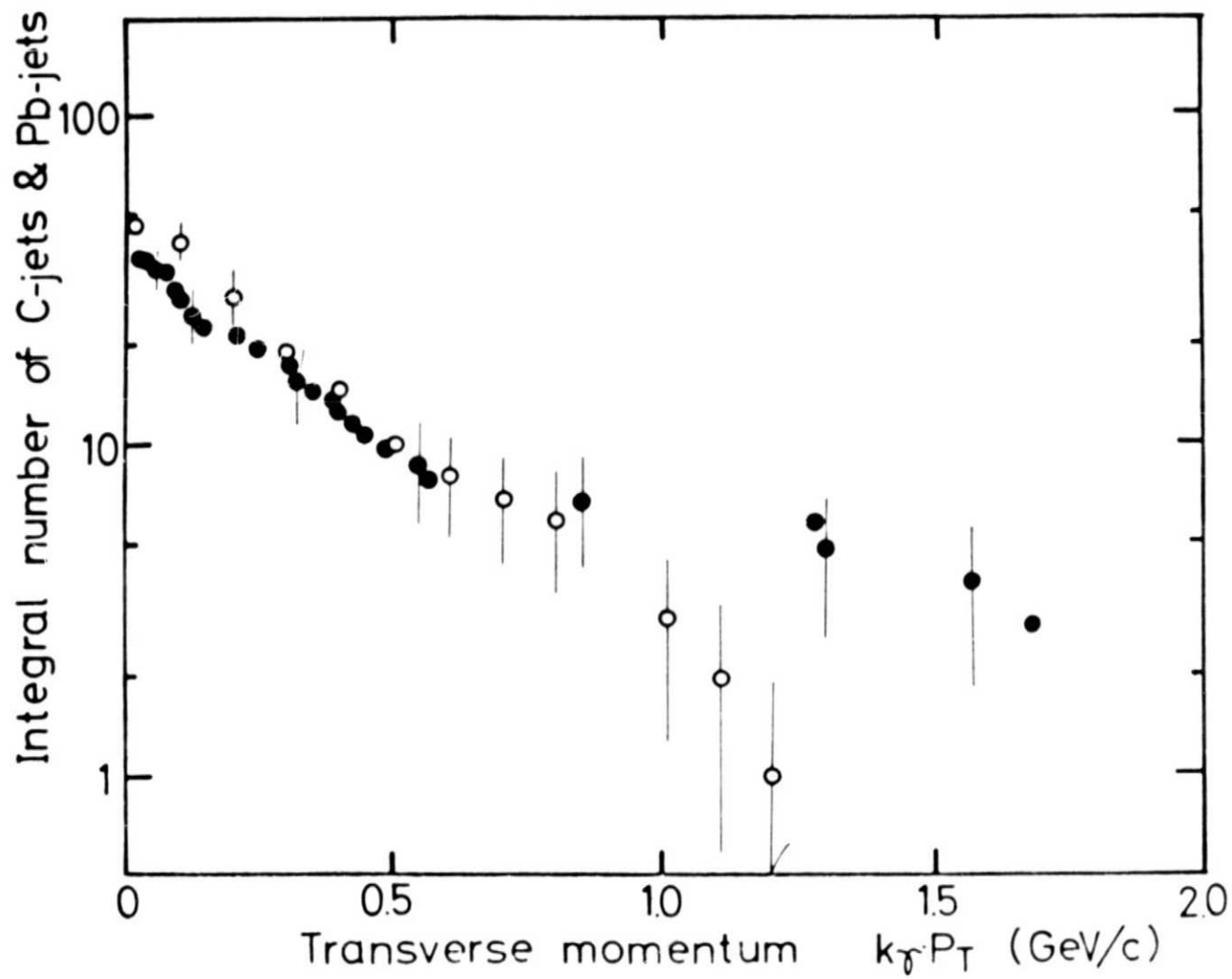


Figure 8

CHAM. -15 EVENT  
 $\sum E_{\gamma} = 230.6 \text{ TeV}$

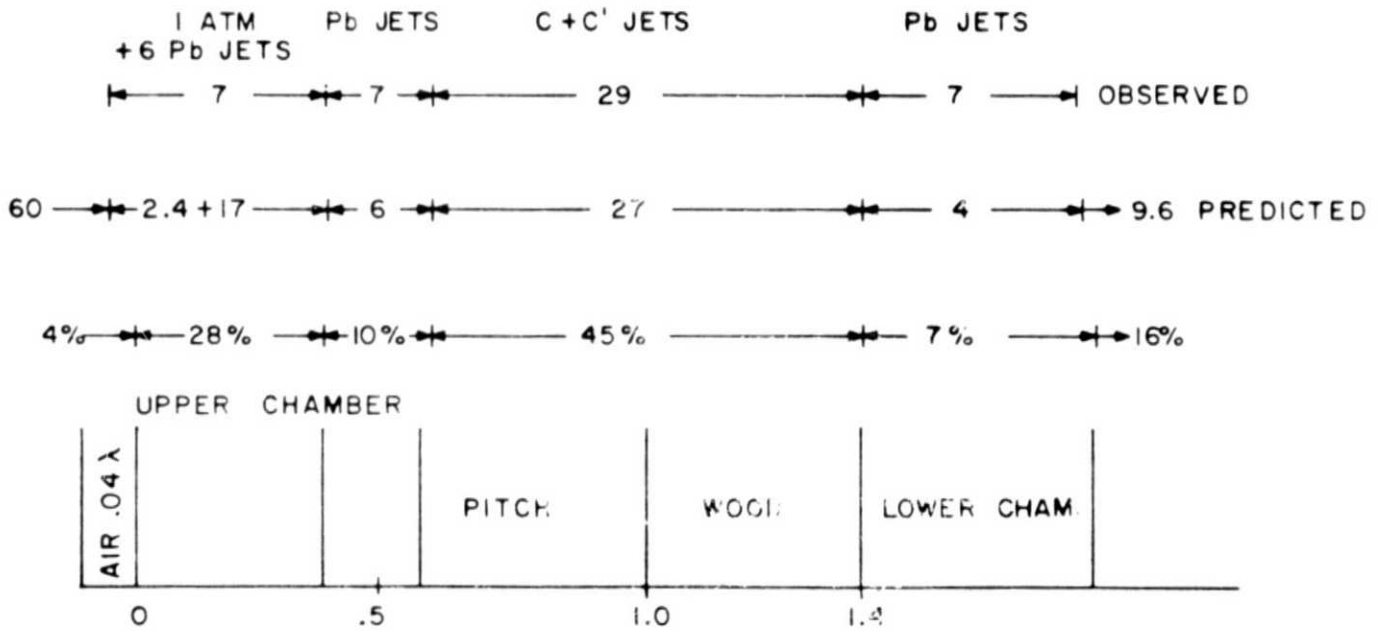


Figure 9

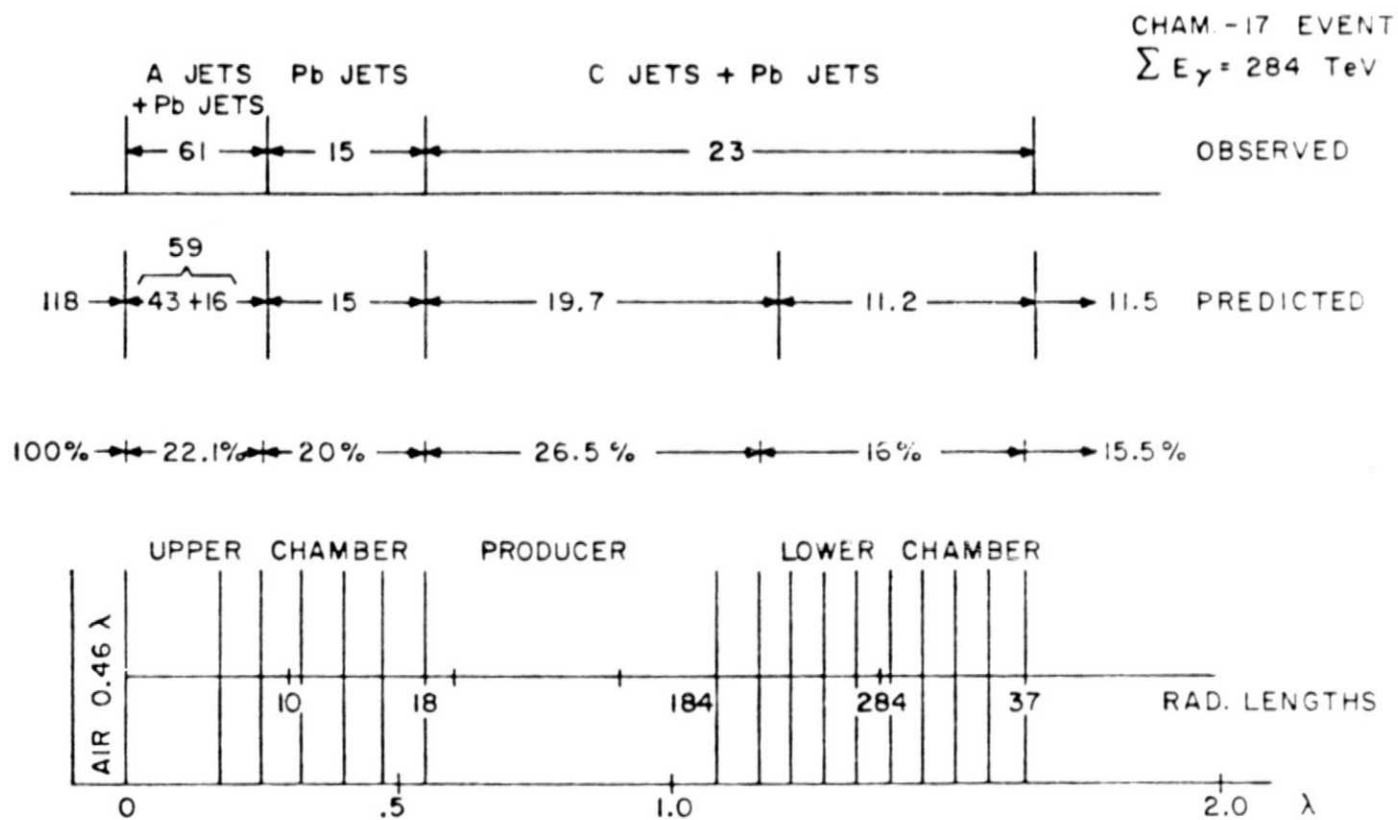


Figure 10

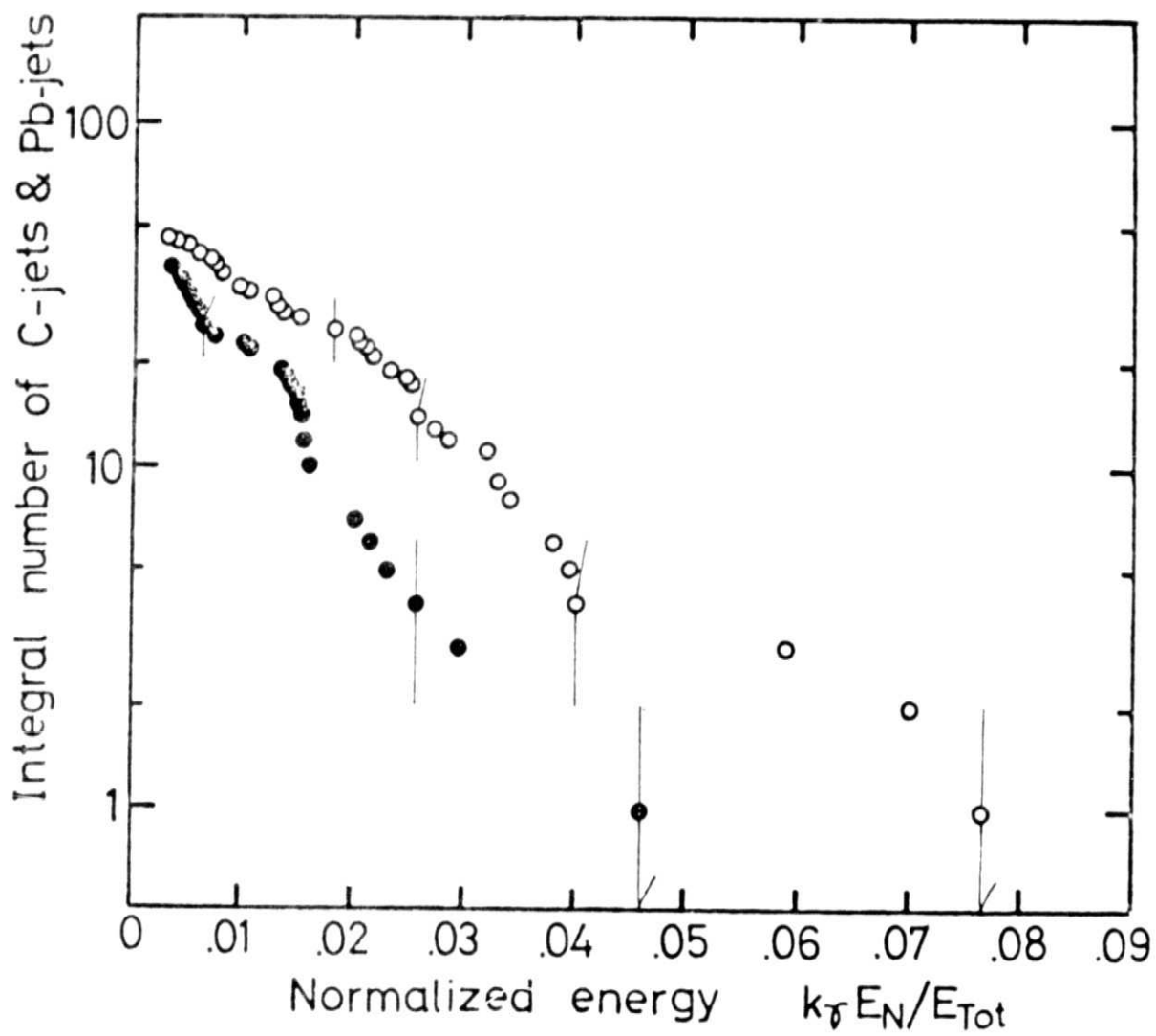


Figure 11

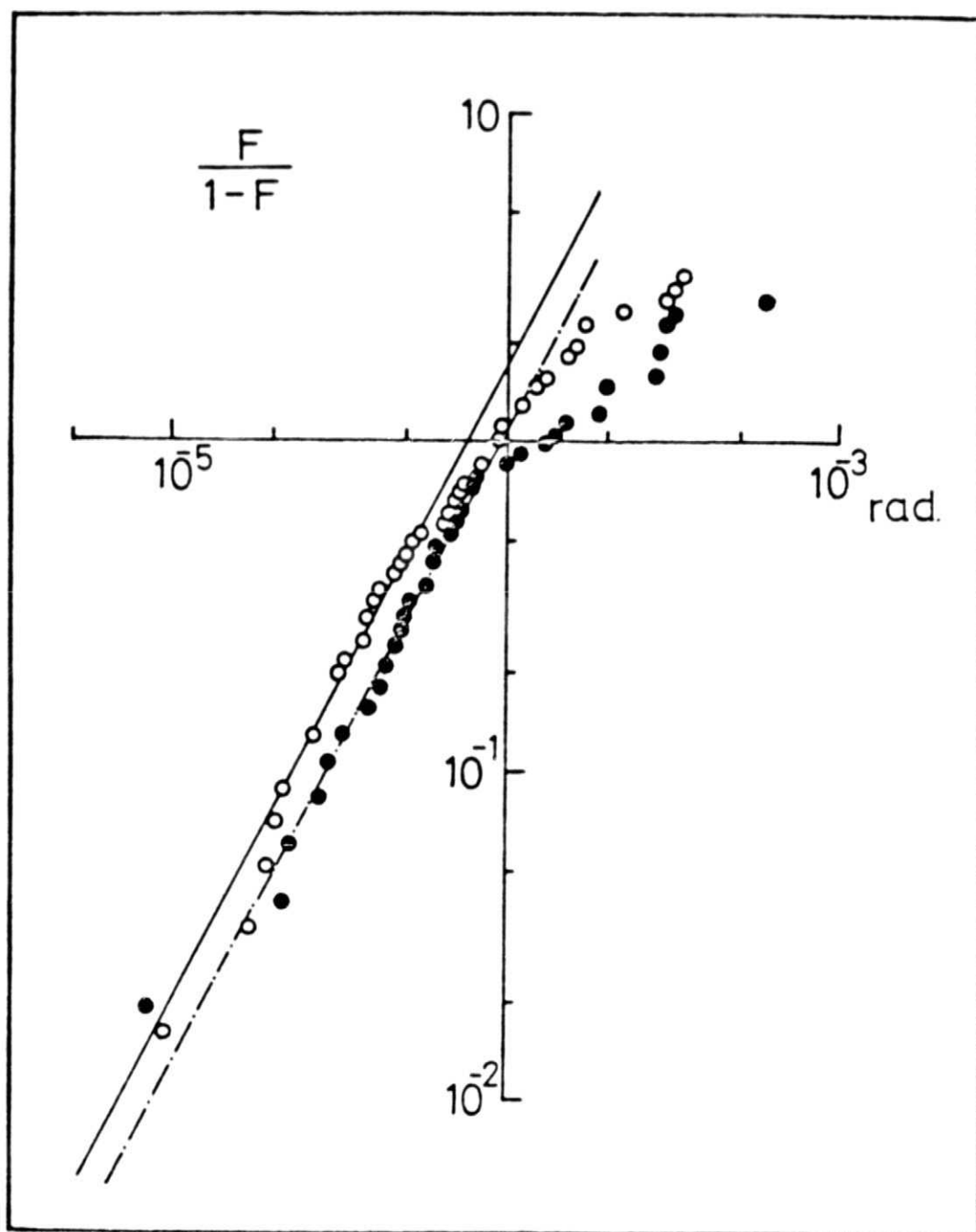


Figure 12

ISA RANGE

3  $\gamma$ -FAMILIES LOWER BOUND

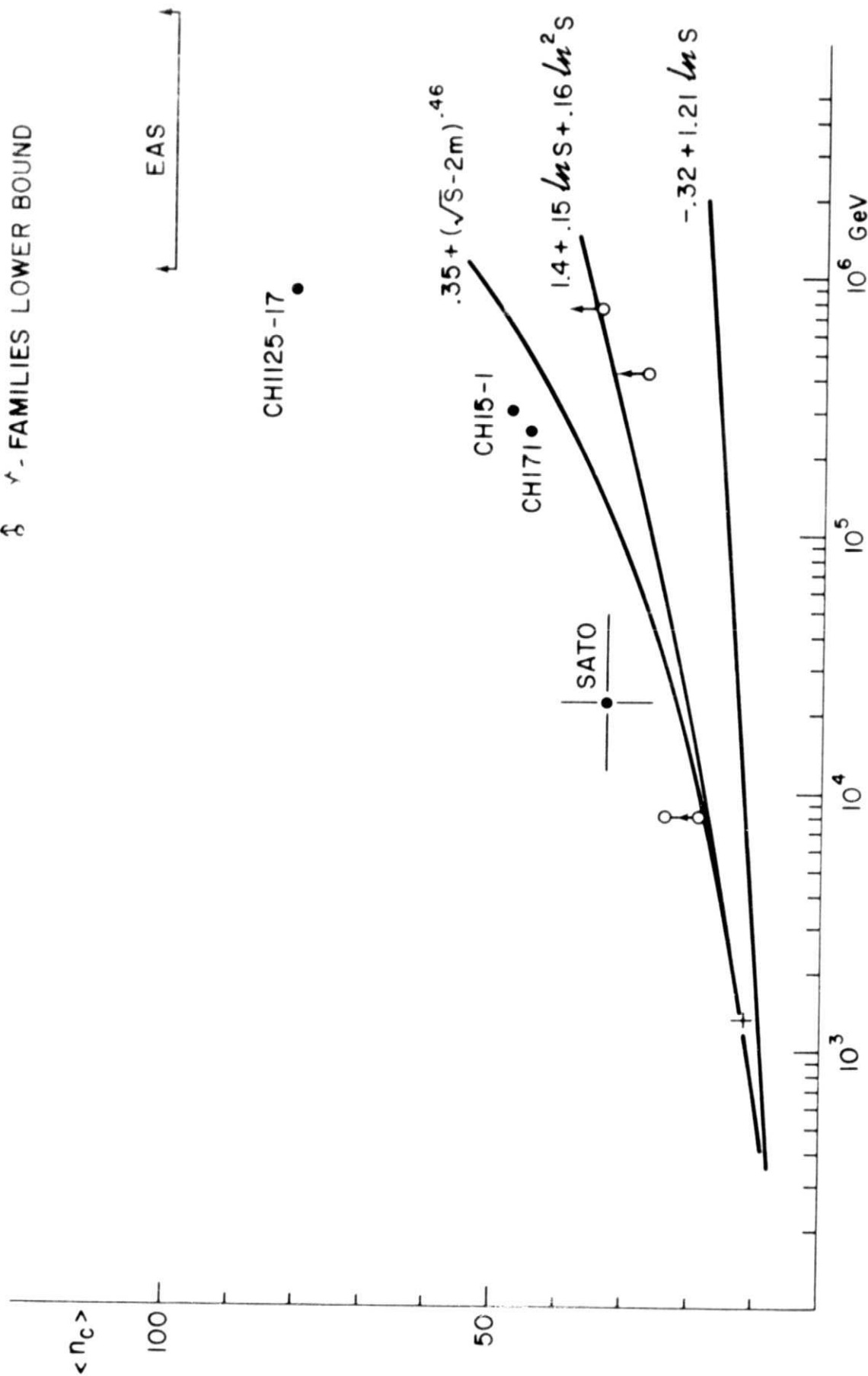


Figure 13